

**DISTRIBUTED GENERATION DRIVETRAIN (DGD) CONTROLLER FOR APPLICATION TO
WIND TURBINE AND OCEAN CURRENT TURBINE GENERATORS**

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to application serial number 09/552,577 of Dehlsen, et al. filed 4/19/00 entitled "Distributed Powertrain For High Torque, Low Rpm, Electric Power Generator", and provisional application serial number 60/222,149 of Stricker, et al. filed 8/1/2000, entitled "Distributed Generation Drivetrain (DGD) Controller For Application To Wind Turbine And Ocean Current Turbine Generators" both assigned to the assignee of this invention, and incorporated herein by reference.

BACKGROUND OF THE INVENTION

Field of the Invention

This invention relates to electric power-generating devices such as wind turbines and ocean current turbines, and more particularly to a method and apparatus for taking the mechanical output of a low rotational velocity high-torque wind or water turbine and converting that to 3-phase electrical power to a utility line.

Description of the Prior Art

Many electric power-generating devices, such as wind turbines and ocean current turbines, benefit from economies of scale, yielding lower costs for generated electricity with larger power generation per unit. This increase in power is often accompanied by a reduction in rotational velocity of the power-input shaft, resulting in a large increase in torque. Because electric generators require rotational velocities tens to hundreds of times greater than the rotational velocity of the input shaft, a speed-increasing gearbox is often applied between the power-input shaft and the generator.

1 The above-referenced Dehlsen, et al application SN 09/552,577 discloses a powertrain
2 for wind turbines and ocean current turbines which consists of a large, input power shaft-
3 mounted, rotating bull-gear with stationary smaller powertrains mounted around its periphery. The
4 gear teeth on the bull-gear rotate past the teeth on the pinions, causing pinions to turn and deliver
5 power to each smaller powertrain. Alternatively, powertrains are attached in a spindle around the
6 perimeter of a main power input drive shaft, and rotate as the shaft rotates. The input drive shaft
7 to each of the smaller powertrain gearboxes is fitted with a pinion. As the main power input shaft
8 turns, the generators, gearboxes and pinions rotate, moving the pinions around the interior of a
9 stationary ring gear. Reduction and distribution of torque is similar to the rotating bull-gear
10 powertrain. In the bull-gear configuration, each smaller powertrain is stationary, reducing stress
11 caused by rotation.

12
13 The power and control side of the powertrain must take the mechanical output from the
14 individual second-stage gearboxes and produce 3-phase electrical power to a utility line. To
15 perform successfully, this control system must assure a uniform torque load distribution between
16 generators, smoothly connect and disconnect with the utility line, seek maximum operating
17 efficiency, monitor and provide protection for mechanical and electrical parameters operating out
18 of specification, and accommodate input from external systems and operators.

19
20 Therefore, besides generators, the power conversion system requires an appropriate
21 controller to manage these tasks.

22 23 SUMMARY OF THE INVENTION

24 Briefly, the invention is concerned with a control method for use with an electric power-
25 generating device that converts fluid flow of wind or water to electricity. The device includes a
26 rotor having blades that rotate in response to fluid flow; a main power input shaft coupled to said
27 rotor; a single-stage torque-dividing gearbox coupled to said main power input shaft; said torque-
28 dividing gearbox having a plurality of output shafts located around a perimeter of said main power

1 input shaft; and, a plurality of sub-powertrains, each one of said sub-powertrains including a
2 generator coupled to a respective one of said torque-dividing gearbox output shafts, the control
3 method comprising regulating torque experienced by each said generator to assure that torques
4 are balanced between generators at any given system load.

5
6 In accordance with an aspect of the invention, the regulating step includes controlling
7 local voltage at each said generator by a transformer configured as a reactor, in which coils of
8 said transformers are wired in parallel and are actively modulated with an SCR, solid-state,
9 switching device.

10
11 In accordance with another aspect of the invention, each generator is connected to a
12 respective primary coil of a transformer and a respective secondary coil is connected to an SCR.

13 14 **BRIEF DESCRIPTION OF THE DRAWINGS**

15 The invention will be described in detail with reference to the drawings in which:

16 **FIGURE 1** is a schematic view of the preferred embodiment of the distributed powertrain
17 control system;

18 **FIGURE 2** shows a schematic view of the induction of the present invention in parallel
19 configuration;

20 **FIGURE 3**, is a schematic view of a generator voltage control circuit in one-line
21 configuration;

22 **FIGURE 4** is a diagram of a 60 Hz sine wave with SCR-T modulation; and,

23 **FIGURE 5** is a schematic diagram of a SCR-T control scheme.

24 25 **DESCRIPTION OF THE PREFERRED EMBODIMENTS**

26 **FIGURE 1** is a schematic view of the preferred embodiment of the distributed powertrain
27 control system. The apparatus of SN 09/552,577 via a torque-dividing gearbox distributes a high
28 input torque of a rotor between multiple powertrains, each consisting of a smaller conventional

1 torque-reducing gearbox and generator. The sum of the power producing capacities of the
2 generators is equal to the maximum power delivered by the power-input shaft, and is equivalent
3 to the power produced by a single generator in a conventional system. This apparatus is referred
4 to herein as a distributed generation drivetrain or DGD.

5
6 The present control system design incorporates an embedded, real time controller
7 orchestrating control tasks with a host computer linked to it via a high-speed network. The host
8 acts as the data-logging device and serves as the user interface, thus freeing the controller to
9 attend to time-critical control functions without distraction. The host stores dynamic performance
10 data to disk while its keyboard, mouse and display provide the operator with real-time status and
11 the ability to initiate commands to the controller. When installed on a wind or ocean current
12 turbine, this control system is integrated into the turbine's controller.

13
14 Induction generators have been identified as a desirable generator style for use as the
15 mechanical-electrical power conversion on the DGD. Induction units were selected due to their
16 low cost and suitability in a wind turbine loads environment. For the purposes of this specification,
17 an example 200 kW DGD system consisting of five, 40 kW generators is presented. It will be
18 understood by those skilled in the art that the DGD may be configured with any number of
19 generators and sized for any desired power output.

20
21 These five generators are configured in parallel on a 480 Volt AC circuit. Arranged as
22 such, each generator operates at 480 Volts (nominally) and the current from each sums to
23 produce the total current output (see **FIGURE 2**). If the torques are balanced the current output
24 from each generator is equal, making the DGD's total current equal to five times the output of a
25 single generator resulting on a total power output of 200 kW. Ultimately the existence of these
26 five generators is transparent to the line as it sees only a single, three-phase output.

27

Synchronous generators have been less successful than induction units on wind turbines due to problems of speed control in gusting winds, and the requirement that the prime mover exactly match synchronous speed. However, it will be understood by those skilled in the art that the principles of the invention are applicable to synchronous generators.

Torque Control

An inherent problem with induction generators is the difficulty in manufacturing them on a standard production line to have precisely repeatable slip characteristics. By design, induction generators run faster than synchronous speed by some small percentage (typically 1.5% at full load) known as its slip, but from one unit to the next this slip varies by a small amount (nominally plus or minus 0.2%). On a 1200 RPM design this amounts to a possible variation of 5 RPM between generators with a nominal full slip range of 18 RPM; since the power output goes from zero at 1200 RPM to full load at 1218 plus or minus 2.5 RPM. This slip variability has a huge impact on the load sharing of generators all being driven at exactly the same speed. Thus, the heart of the DGD control function is to regulate the torque experienced by each induction generator and assure that the torques are balanced between generators at any given system load.

Various techniques of torque control for the DGD are possible. Both passive tuning and active control methods are possible. The more practical and cost effective of these are described in the paragraphs, which follow.

Series Resistance In The Rotor Circuit

A small series resistance is added in the rotor circuit. Increasing the rotor resistance has the effect of increasing the slip. In this case the slip characteristic of each generator is modified to match the unit with the greatest slip. This method is practical with wound rotor designs and may incur some, presumably small, resistive power loss. In addition, dynamometer testing of each generator is required for tuning resistance.

1

2 **Using Inductors And Capacitors To Modify Generator Voltage**

3 In this method inductors and capacitors are used to modify generator voltage. The
4 inductors are configured to partially isolate each generator from the others and create a local
5 voltage environment. The capacitors are then applied in parallel to each generator's local voltage
6 environment to raise its voltage as needed. Since induction generators have an inherently lagging
7 power factor, the addition of capacitive VAR support raises the voltage proportionately ("VAR
8 support" is a common term in the utility industry, referring to the use of capacitance to offset
9 lagging power factor and raise voltage on utility lines.) Raising the voltage tends to reduce slip,
10 thus a prescribed capacitance is added to each generator to match the generator with the least
11 slip. Adding capacitance has the secondary benefit of improving the power factor. Limitations to
12 this technique are that dynamometer testing of each generator is required for tuning capacitance
13 to determine how much capacitance is necessary to have the desired effect.

14

15 **Configuring The Generators To Be Wired In Series.**

16 With this method all of the current passes through each generator and the voltage
17 applied to each unit is nominally equal to 480 volts divided by the number of generators on line.
18 The actual voltage at each generator varies depending on its relative slip characteristic, but
19 because the current is exactly the same through all generators, the input torques are also
20 precisely matched. Additional cost is incurred with this design because it requires that the
21 generator windings be sized to carry the full rated system power. The generators must also be
22 designed to be efficient over a wide range of applied voltages, depending on the number of
23 generators on line.

24

25 **Utilizing Silicon Controlled Rectifiers (SCRs)**

26 In this method, Silicon Controlled Rectifiers (SCRs) and parallel-connected transformers
27 are used to actively control generator voltage. Because this design allows full, active control of
28 torque at all power levels, it is the preferred method over other torque balancing methods. A full

range of operational performance can be evaluated with this control approach. If a fixed slip adjustment appears to resolve the torque balance issue over a range of power levels, as demonstrated with this controller, then passive-tuning methods may be employed. In addition, active control provides other functionality such as soft-starting and over torque protection for the DGD. This SCR-Transformer controller is described in detail in the following section.

SCR-Transformer Torque Controller

The key to the cost-effectiveness of the SCR-Transformer (SCR-T) Controller is a fundamental property of induction generators that greatly facilitates voltage regulated torque control, namely, torque is proportional to voltage squared. This relationship implies that only a small voltage change is required to produce a significant effect on torque. Thus, only minor variations from nominal line voltage will provide the necessary torque balance between generators, and the equipment required to modulate voltage is proportionately reduced in cost. To achieve control over the local voltage at each generator, a transformer (configured as a reactor, i.e. the coils are wired in parallel rather than series) is actively modulated with an SCR, solid-state, switching device. This concept applied to induction motor soft-starting is described in a paper by Walter Mientrup, "Siemens Power Engineering," Vol. II, No. 3, March 1980, pp 83-85. This arrangement is shown in **FIGURE 3** as a one-line diagram of the example 200 kW system. The generator is connected to the "primary" coil of this transformer and the "secondary" is connected to the SCR.

The function of this system relies on the reactance of the primary transformer coil, which with no air gap in the core (see the next section on SCR-T Controller Design) would reduce the voltage at the generator to nearly zero when the secondary coil is open-circuited. As it is however, the presence of the air gap allows the "open-circuited" generator voltage to be some fraction of the line voltage (for example 80%). On the other hand, the shorted secondary condition allows full line voltage to appear on the generator. Thus when the SCR is gated on, full voltage is conducted to the generator and when it is off 80% of full voltage is conducted.

1

2 Because of the binary operation of the SCR, only two voltage states are possible at the
3 generator terminals at any instant. Nonetheless, using pulse width modulation (PWM) techniques,
4 the SCR may be gated on and off for a portion of the 60 Hz cycle allowing an *average* voltage
5 between 80 and 100%. Thus, by adjusting the duty cycle of SCR gating, any voltage between 80
6 and 100% may be attained in order to satisfy immediate torque requirements. A plot of the 60 Hz
7 waveform with the SCR-T controller managing the duty cycle is shown in **FIGURE 4**. Those
8 skilled in the art will realize that this technology may be applied to a 50 Hz line frequency as
9 easily as to 60 Hz line frequency.

10

11 The control loop regulating torque first looks at the average of the three phase currents
12 being produced by the generator then calculates the equivalent torque based on current. As soon
13 as all generators have had the same readings and calculation performed, they are compared to
14 determine the relative torque loading of each. Based on the relative torque ratios and the squared
15 relationship of voltage to torque, the duty cycles of each of the fifteen SCRs (three phases of the
16 example five generators) are adjusted to provide the proper voltage to bring the torques into
17 balance. This loop executes fairly quickly (say at 10 Hz, using six readings taken and averaged
18 once per cycle of the 60 Hz line) assuring that the torque balance is continuously maintained.

19

20 **SCR-T Controller Design**

21 In addition to the controller architecture described previously, the SCR-T controller
22 requires transformers, SCRs, high-speed current transducers, and SCR control boards to
23 complete the system. The necessary I/O is limited to current transducer (analog) inputs for each
24 phase current and analog output voltages to the SCR control boards dictating the desired voltage
25 levels. A circuit diagram of the SCR-T control system is shown in **FIGURE 5**. Note that capacitors
26 have been added to the output leads to correct the power factor to 0.95 for improved power
27 quality. The design of the transformer involves specifying the following parameters to achieve the
28 desired reactance and current carrying capabilities:

- 1 The required number of primary and secondary turns
- 2 The primary and secondary conductor sizes
- 3 The quantity and configuration of core iron
- 4 The size of the core air gap

5

- 6 The core geometry must include an air gap to lower the zero-state reactance. The size of
- 7 this air gap in the magnetic circuit determines the magnitude of the reactance and thus the ratio
- 8 between the coil reactance and the generator impedance. The relationship between coil
- 9 reactance and generator inductance establishes the residual voltage to the generator when the
- 10 SCRs are open circuited, which represents the control circuit's minimum voltage range.

11

12 **SCR-T Controller For Wind Gust/Current Surge Control**

- 13 Another import facet of the torque regulation capabilities of the SCR-T controller is its
- 14 ability to increase/decrease slip by reducing torque, in response to variations in the prime mover
- 15 input torque. This capability is especially significant to wind and ocean current turbine control
- 16 where variations in the input torque occur on a regular basis as the rotors are subjected to wind
- 17 gusts and surges in ocean current velocity.

18

- 19 Using the same principle and equipment that is applied to individual generator torque
- 20 balancing on the DGD, overall torque modulation is simply achieved with another control loop.
- 21 This loop operates outside of the torque-balancing loop and looks at the net current being
- 22 produced (i.e. I_{total} in **FIGURE 2**) to control the total reaction torque produced by the generators.
- 23 When the SCR-T controller sees a rising current, it responds by lowering its torque command to
- 24 the SCR control boards, which in turn reduces the duty cycle on the signals to the SCRs. The net
- 25 effect is that rising current (indicating rising input torque) causes the controller to command a
- 26 decrease in generator reaction torque and an increase in slip. The ability to vary reaction torque
- 27 in response to wind gusts or current surges allows the energy in the gust or surge to be converted
- 28 to rotor inertia. The lowered reaction torque produces increased generator slip and thus higher

1 rotor speed. As the gust or surge passes, the controller then increases the reaction torque back
2 to its nominal value, thereby reducing the slip, and the excess rotational inertia is converted into
3 torque. The significant value of this control strategy is that torque spikes caused by gusts or
4 surges which would normally be borne directly by the drivetrain, are instead converted to rotor
5 inertia and then converted to torque when the input torque spike has diminished. Essentially, the
6 rotor is momentarily being used as a flywheel to store excess energy until the input loads come
7 back down to nominal, at which point this inertial energy is allowed to enter the drivetrain. Aside
8 from smoothing the gust or current surge effect on the output power, reducing the magnitude of
9 torque spikes experienced by the mechanical components in the drive train reduces spike
10 induced damage and/or allows the gearbox to be designed for lower peak loading. This control
11 method, then, applies to multiple, induction generator powertrains such as the DGD, with torque
12 balancing being conducted between generators, as well as to systems with only a single induction
13 generator and drivetrain (which, of course, does not utilize a torque balancing algorithm). In all
14 cases this gust/surge control algorithm has the effect of smoothing momentary, excess torque
15 events and reducing the peak torque carried by the powertrain.

16
17 While the invention has been particularly shown and described with reference to
18 preferred embodiments thereof, it will be understood by those skilled in the art that the foregoing
19 and other changes in form and detail may be made therein without departing from the scope of
20 the invention.